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SPECTRAL IRRADIANCE MEASUREMENTS OF LARGE SOLAR SIMULATORS

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16. Abstract

The statistical extrapolation of spectral irradiance data for a large solar simulator is discussed. This extrapolation is performed to allow prediction of the spectral irradiance of some point in the solar beam that has not been measured directly.

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SPECTRAL IRRADIANCE MEASUREMENTS OF LARGE SOLAR SIMULATORS

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SUMMARY

By making use of broad-band spectral irradiance measurements made with filter radiometers, the spectral irradiance of a large-scale solar simulation system can be predicted by statistically extrapolating narrow-band measured data. The uncertainties involved in extrapolating the measured narrow-band data to the points in the solar simulator array where only broad-band measurements have been made are discussed.

INTRODUCTION

Many systems and spacecraft in the Gemini Program, the Apollo Program, and future spacecraft programs have been, or will be, qualified by thermal-vacuum tests. An essential function of these tests is to determine the thermal response and thermal balance of the test article by irradiating the article with a simulated solar flux in a thermal-vacuum environment. To determine the thermal energy input to the test article, it is necessary to know the total intensity and the spectral distribution of the simulated solar flux. The purposes of this report are to describe a method of measuring the spectral distribution of the flux of a large-scale solar simulator and to analyze the uncertainties in the measured data and in applying the measured data. Emphasis is placed on the problems involved in determining the ultraviolet component of the spectral distribution.

MEASUREMENT REQUIREMENTS

Large solar simulation systems are basically of two types: the single-beam, off-axis system and the multibeam, on-axis modular system. These large solar simulation systems have inherent spectral-distribution-uniformity problems. In the on-axis modular simulator, each solar simulator module contains a Cassegrain collimator coupled with a source and collector system. A combination of refractive and reflective elements in the module optical train produces three distinct spectral zones in the output flux of each solar simulator module (fig. 1). In addition, minor spectral variations exist within each zone and at the interfaces of the zones. Because of these variations in the flux spectral distribution of a solar simulator module, it is necessary to make a

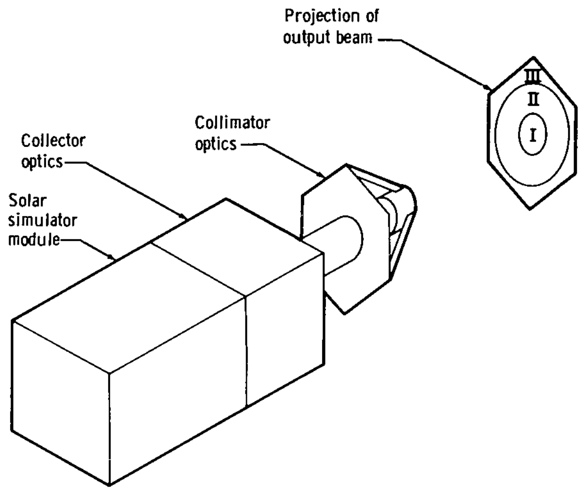

Figure 1. - On-axis solar simulator module configuration showing zones of spectral variations.

series of measurements for each module in an array of modules to provide the necessary data to evaluate the overall spectral distribution of the array. As a result of time and manpower limitations, it is generally not feasible to make continuous spectral monochromator measurements over an entire array. Therefore, a method has been devised by which continuous spectral monochromator measurements are made on a single solar simulator module and then coupled with broad-band-filter radiometer measurements made over the face of the array to determine the flux spectral distribution for other points in the array where no spectral data were measured. This manipulation of the spectral data will be referred to as spatial extrapolation.

MEASUREMENT METHOD

The basic requirement for performance of the spatial extrapolation of the measured continuous spectral monochromator data is the determination of the spectral nonuniformity of the solar simulator output beam. This nonuniformity is determined by making broad-band-filter radiometer measurements over a grid network in a plane normal to the output beam. A filter spectroradiometer is positioned at each discrete point in the grid, and a spectral distribution measurement of the solar simulator flux is made for each location. The filter spectroradiometer is equipped with a total-energy detector and four band-pass filters that allow the splitting of the spectrum into five spectral bands. The wavelength limits of these bands are 0.22μ to 0.388μ, 0.388μ to 0.688μ, 0.688μ to 0.89μ, 0.89μ to 1.87μ, and 1.87μ to 4.0μ. The energy in each band is divided by the total energy in the spectrum to obtain the percentage of energy in each band. This operation, in effect, provides a spectral distribution of the solar simulator flux normalized to 1 solar constant for each measurement location.

The narrow-band monochromator measurements are made at several locations within the single solar simulator module. One set of measurements is generally made in each spectral zone, with additional measurements being made in any other locations within the module as necessary for any particular test article or safety requirement.

In making continuous spectral measurements, the monochromator is set up so that it intercepts the radiant flux being measured after it is reflected off a flat magnesium oxide diffuser (fig. 2). The magnesium oxide diffuser is a highly diffuse reflector that integrates the energy entering the monochromator to eliminate sharp spatial gradients over the sensor surface. These gradients occur when the monochromator views a finite-sized source. The flat magnesium oxide diffuser is used rather than an integrating sphere in these measurements because the magnesium oxide diffuser is about

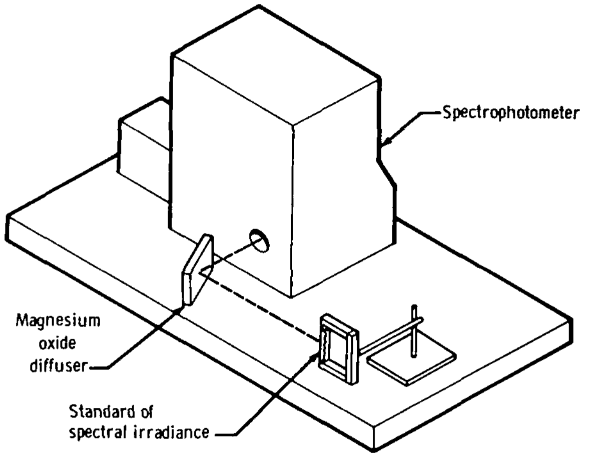

Figure 2. - Spectrophotometer calibration setup.

10 times more efficient than an integrating sphere and therefore allows better accuracy in measuring the low flux levels in the ultraviolet wavelengths (ref. 1). Although the magnesium oxide diffuser is more efficient than the integrating sphere and provides a higher output signal from the monochromator, the magnesium oxide diffuser has several disadvantages that must be considered. These factors are discussed in the section of this report entitled "Measurement Uncertainties."

A transfer function or transfer efficiency of the monochromator-diffuser system must be determined for each series of spectral measurements. This value is determined by placing a calibrated National Bureau of Standards (NBS) standard of spectral irradiance in front of the diffuser and determining the output of the monochromator for the known irradiance of the standard lamp. This step is of primary importance since it limits the maximum accuracy to which the spectral distribution of the solar simulator flux can be determined. Once the transfer function of the monochromator-diffuser system has been determined, the continuous spectral measurements are made at each desired location in the solar simulator module.

The data from the standard-lamp scan and the solar-simulator-module scans are broken into narrow bands of 100 to 500 angstroms, depending on the wavelength resolution of the monochromator over the wavelength region. The energy in each band is computed, and the sum of the bands is normalized to 1 Solar Constant and plotted against the normalized Johnson curve of the Solar Constant for zero air mass.

MEASUREMENT UNCERTAINTIES

The uncertainty in the solar simulator spectral distribution data is of two categories. The first category is the uncertainty in the measured continuous spectral data for a single discrete position in an array, and the second category is the uncertainty added to the measured data when the previously mentioned spatial extrapolation is performed to determine the spectral distribution at some other position in the array. The uncertainties in the measured continuous spectral data are derived from three major sources: standard-lamp and monochromator calibration uncertainties, solar simulator temporal instability, and measurement uncertainties due to instrument setup and operating techniques. The total uncertainty in the measured continuous spectral data can be determined by taking the root of the sum of the squares (RSS) average of the individual uncertainties associated with the data (ref. 2). The uncertainty associated with the spatial extrapolation of the measured continuous spectral data is due to spatial variations in the spectral distribution of the solar simulator flux. This variation in spectral distribution exists to varying degrees in both the plane of the array and in depth. The total uncertainty in spatially extrapolated data can be determined by taking an RSS average of the uncertainty in the measured continuous spectral data and of the uncertainty associated with the spatial extrapolation of the measured data. The resultant is the definition of the accuracy attainable in the solar simulator spectral distribution data at a discrete position and the definition of the uncertainty added to these data when they are spatially extrapolated to some other position in the array.

As indicated previously, an NBS standard of spectral irradiance is used to calibrate the monochromator-diffuser system for each series of measurements. The standard lamp is a 1000-watt quartz-halogen lamp with a coiled-coil tungsten filament that operates at approximately 3000° K. The standard lamp is calibrated over the wavelength range of 0.25μ to 2.6μ by comparison with an NBS standard lamp that has been calibrated against a high-temperature black-body source. The spectral irradiance of the standard lamp is primarily dependent upon the filament temperature, which is a function of the electrical current flowing through the filament. Difficulties in making accurate black-body comparisons and difficulties in making precise filament current settings account for the uncertainties in the standard-lamp calibration. These uncertainties vary from approximately ±8 percent at the shortest wavelengths in the ultraviolet region to approximately ±3 percent in the visible and infrared regions (ref. 3). These uncertainties in the standard-lamp calibration effectively establish a lower limit on the accuracy to which the monochromator-diffuser system can be calibrated and on the accuracy to which the spectral distribution of the solar simulator flux can be measured.

Additional uncertainties in the monochromator calibration are introduced through the calibration procedures of setting up and measuring the output of the standard lamp. As mentioned previously, the light from the standard lamp is reflected off a magnesium oxide diffuser onto the entrance slit of the monochromator. Since the magnesium oxide diffuser is a flat plate, uncertainties arise in determining the actual distance from the standard lamp to the surface of the diffuser. This problem can be eliminated with the use of an integrating sphere in place of the magnesium oxide diffuser, but the poor efficiency of the integrating sphere causes difficulty in measuring the low-ultraviolet flux levels. The increased efficiency of the flat magnesium oxide diffuser and the corresponding higher output signal outweighs the slight increase in accuracy achievable with the integrating sphere. Although the magnesium oxide is a good diffuse reflector, its reflectance degrades with exposure to ultraviolet radiation or a high-humidity environment (or both). The rate and degree of this degradation is significant for freshly prepared surfaces, but the rate of degradation reduces as the surface ages (ref. 4). For a surface which is at least 7 days old, the degradation in reflectance over a 1- or 2-day period would not cause appreciable uncertainties in spectral data obtained over this period. The measurement accuracy of the monochromator is also a significant accuracy factor. If one type of spectrophotometer (out of the many types available) is used to make the measurements, a small measurement uncertainty on the order of ±2 to ±3 percent is introduced.

An additional factor contributing to the uncertainty in the measured continuous spectral data is the temporal instability of the simulator source. Variations with time of a carbon-arc source can be on the order of 3 to 4 percent. Although this temporal variation does not affect the accuracy of the narrow-band measurement directly, it becomes important when the data are used to define the spectral distribution of the solar simulator flux at this point at some subsequent point in time.

The total uncertainty in the measured continuous spectral distribution data is determined by taking an RSS average of the individual uncertainties associated with the monochromator calibration and of the solar simulator temporal instability. This step results in a total uncertainty in the measured data of approximately ±12 percent for the ultraviolet wavelengths and ±6 percent for the visible and infrared wavelengths.

Figure 3 is a plot of the measured spectral irradiance data (table I) for a carbon-arc module. The uncertainty in the measured data is included in the curve to illustrate the error band for the measured data.

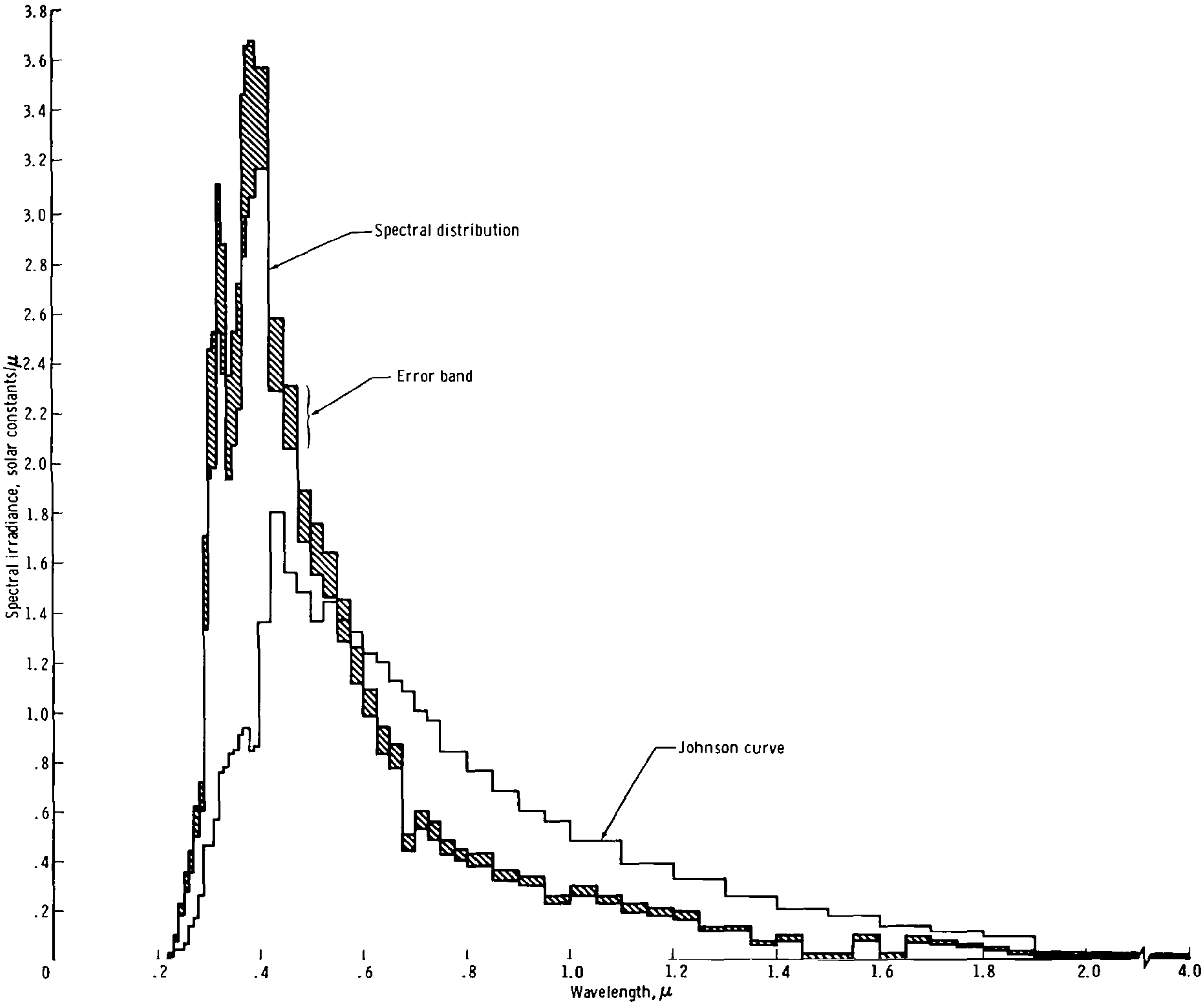

Figure 3. - Solar simulator spectral distribution showing uncertainty in measured data.

TABLE I. - SPECTRAL IRRADIANCE OF ZONE I OF THE SOLAR SIMULATOR MODULE

Wavelength range, μ	Johnson curve J, solar constants/μ (a)	Measured data J, solar constants/μ (a)	Wavelength range, μ	Johnson curve J, solar constants/μ (a)	Measured data J, solar constants/μ (a)
0.22 to 0.23	--	0.020	0.675 to 0.700	1.08	0.474
.23 to .24	0.04	.089	.700 to .725	1.00	.564
.24 to .25	.04	.200	.725 to .750	.96	.515
.25 to .26	.07	.316	.750 to .775	.84	.459
.26 to .27	.14	.396	.775 to .800	.84	.425
.27 to .28	.17	.556	.800 to .85	.76	.403
.28 to .29	.26	.686	.85 to .90	.68	.344
.29 to .30	.46	1.527	.90 to .95	.60	.324
.30 to .31	.46	2.202	.95 to 1.00	.56	.248
.31 to .32	.57	2.244	1.00 to 1.05	.48	.278
.32 to .33	.76	2.810	1.05 to 1.10	.48	.247
.33 to .34	.78	2.625	1.10 to 1.15	.39	.217
.34 to .35	.83	2.147	1.15 to 1.20	.39	.201
.35 to .36	.84	2.293	1.20 to 1.25	.33	.183
.36 to .37	.91	2.469	1.25 to 1.30	.33	.133
.37 to .38	.93	3.145	1.30 to 1.35	.26	.131
.38 to .39	.84	3.325	1.35 to 1.40	.26	.079
.39 to .40	.86	3.399	1.40 to 1.45	.21	.102
.40 to .425	1.36	3.367	1.45 to 1.50	.21	.011
.425 to .45	1.80	2.433	1.50 to 1.55	.18	.010
.45 to .475	1.56	2.184	1.55 to 1.60	.18	.096
.475 to .50	1.48	1.786	1.60 to 1.65	.14	.009
.50 to .525	1.36	1.652	1.65 to 1.70	.14	.083
.525 to .55	1.44	1.551	1.70 to 1.75	.12	.075
.55 to .575	1.36	1.374	1.75 to 1.80	.12	.071
.575 to .60	1.32	1.190	1.80 to 1.85	.10	.057
.60 to .625	1.24	1.030	1.85 to 1.89	.10	.036
.625 to .650	1.20	.884	1.89 to 4.00	.026	.0002
.650 to .675	1.12	.821			

[a]The value of the spectral irradiance J has been normalized to a total irradiance of 1 solar constant (138 mW/cm^2).

The uncertainties associated with the spatial variations in the spectral distribution of the solar simulator flux were determined through an analysis of the broad-band data obtained over the plane of the array. This analysis showed variations of +47 and -37 percent from the mean flux value in the ultraviolet wavelengths and variations of ±20 percent from the mean flux value in the visible and infrared wavelengths. These variations were determined without regard to whether the flux fell within zone I, II, or III of the collimators. When the spectral zones of the collimators are considered during spatial extrapolation of the measured data, the uncertainties due to the spatial variations in the spectral distribution are on the order of ±25 to 30 percent for the ultraviolet wavelengths and ±15 percent for the visible and infrared wavelengths. By taking an RSS average of the uncertainty in the measured data and of the uncertainty associated with the spatial extrapolation, total uncertainties of ±32 percent for the ultraviolet wavelengths and ±16 percent for the visible and infrared wavelengths are obtained for each zone of the collimators. Figure 4 is a plot of the measured data from

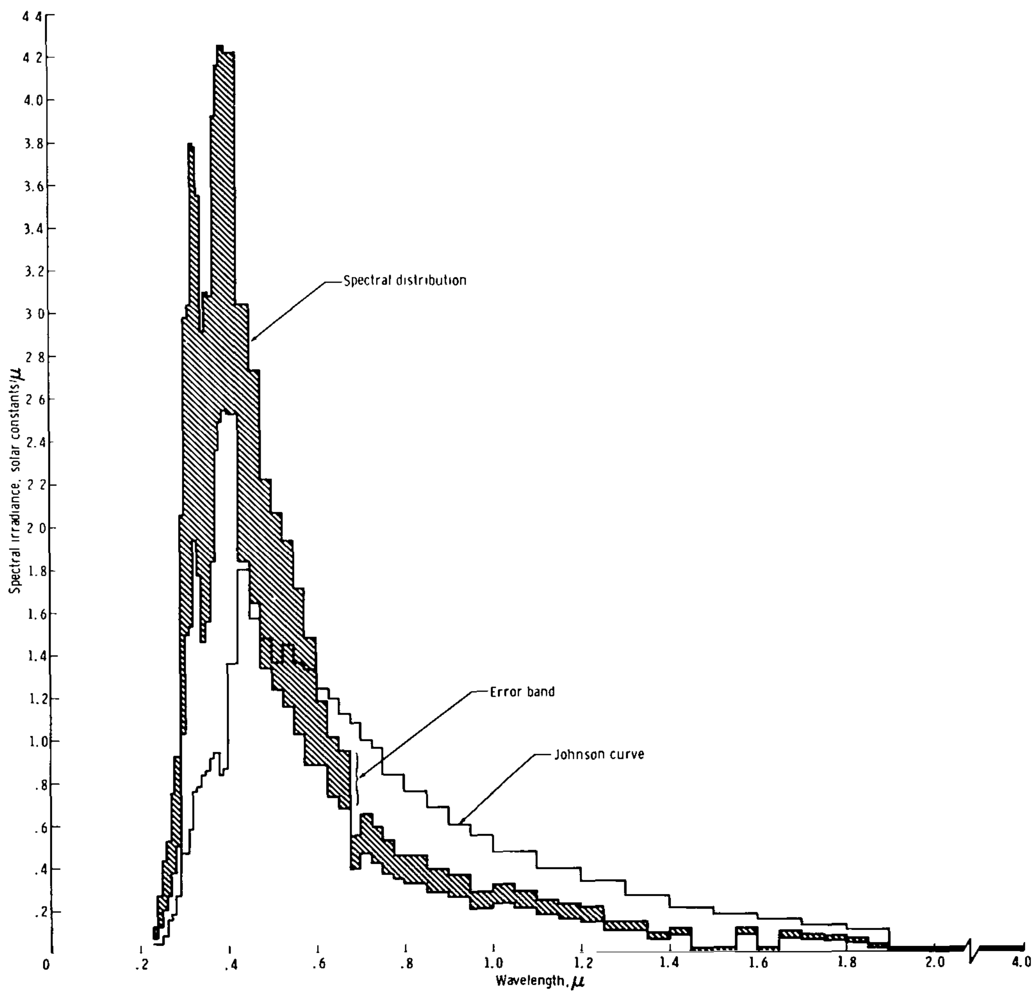

Figure 4. - Solar simulator spectral distribution showing combined uncertainties of measured and spatially extrapolated data.

table I. The total uncertainty for extrapolated data has been included in the plot. The resulting curve in figure 4 is a plot of (1) the spectral radiance of the central zones of the solar simulator modules and (2) the error band to be considered when applying the data.

CONCLUSIONS

One of the primary problems connected with the operation of a large solar simulator is the determination of the spectral characteristics of the solar simulator flux at any point in the output beam. It is not practical to make detailed spectral irradiance measurements over the entire cross section of the beam. Therefore, a statistical analysis method must be employed to provide the necessary solar simulator flux data.

The method described in this report uses a combination of continuous spectral monochromator measurements and broad-band-filter radiometer measurements. The broad-band measurements are used to determine the spatial variations in flux spectral distribution. These spatial variations are then used to spatially extrapolate the continuous spectral monochromator data to any point in the output beam. A statistical analysis of the measurement uncertainties and of the spatial variations in flux spectral distribution allows a determination of the maximum uncertainty in the spectral distribution data at any point. The spatial variation in flux spectral distribution is generally the limiting factor in reducing the uncertainty in the extrapolated data in large systems. Therefore, the more uniform a system, the more accurate the spatial extrapolation technique becomes.

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